## Future AARD Possibilities and Options for NML

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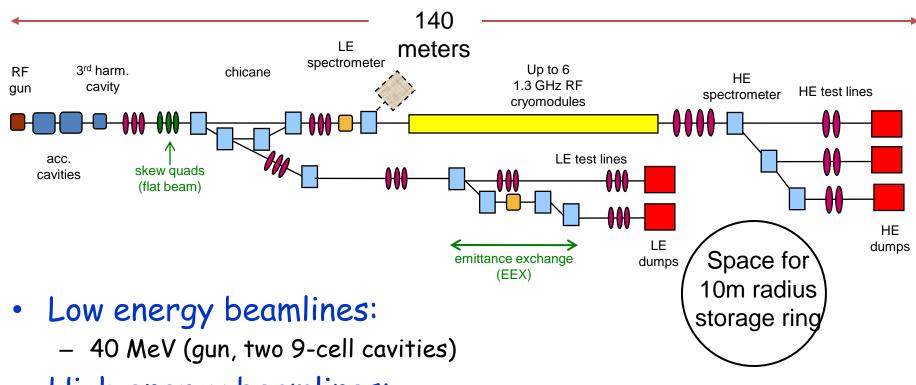
Fermi National Accelerator Laboratory



#### Outline

- New Muon Lab (NML) beamlines for AARD;
- FermiLab's AARD experiences at AO;
- Future AARD Possibilities and Options for NML:
   20 proposals received in previous AARD workshops.
  - Dielectric wakefield acceleration with flat beams (Piot);
  - Test of no-linear integrable optics (Nagaitsev);
  - Emittance partitioning: "flat beam" + "emittance exchange" (Carlsten);
  - Plasma wake field accelerator (Muggli);
  - Compact Muon source test (Striganov);
  - ILC collimator test (Mokhov);
  - Image charge undulator using flat beams (Sun);
  - ...et al.
- Summary

#### Schematic layout of NML beamlines



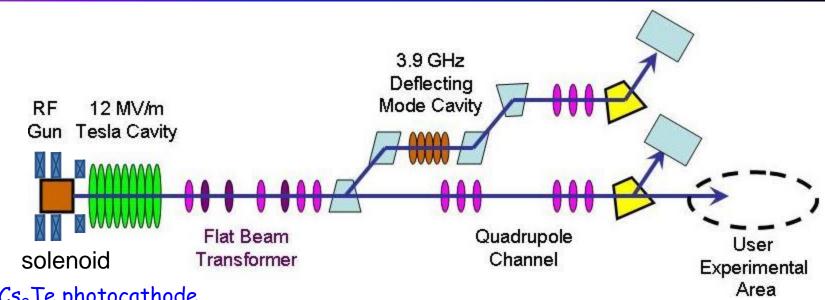
- High energy beamlines:
  - 810 MeV (3 cryomodules);
  - 1075 MeV (4 cryomodules);
  - 1500 MeV (6 cryomodules with radiation shielding considerations),
- Space for a ~10 m storage ring



#### NML Beam Properties

- The New Muon Lab is capable of producing ILC-like beam:
  - 3.2 nC/bunch;
  - 3 MHz bunch rate:
  - 1 ms long bunch train;
  - 300 mm RMS bunch length;
- 5 Hz repetition rate;
- Normalized transverse emittance ≤5 mm @ 3.2 nC;
- Peak currents 10 15 kA possible;
- Maximum charge per bunch 10 nC possible.

#### A0 photoinjector

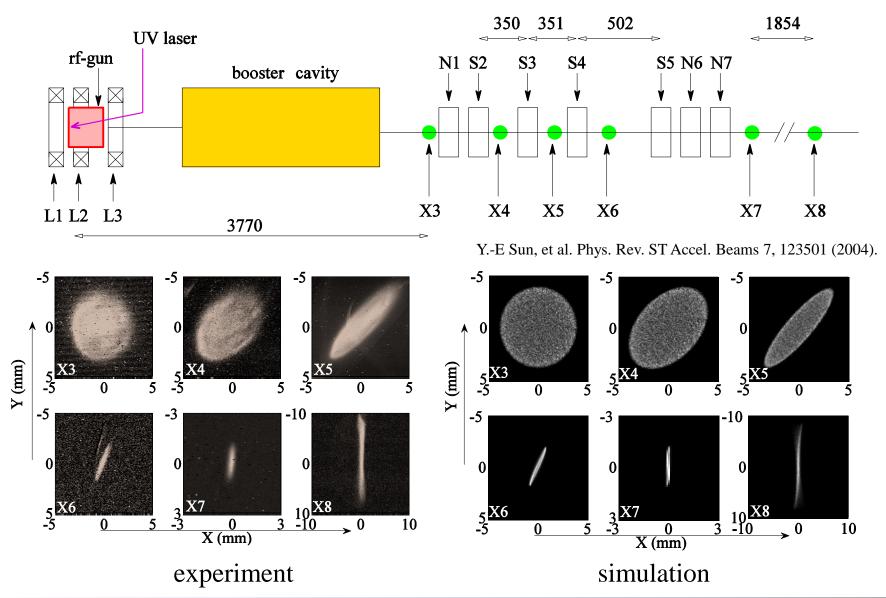


- ·Cs<sub>2</sub>Te photocathode
- ·Nd:YLF drive-laser
- •Typically the bunch charge is set to 1nC, but provided up to 15 nC for PWFA
- •1.5-cell 1.3 GHz NC rf-gun with three solenoids for emittance manipulation
- •9-cell TESLA-type booster cavity
- ·Beam energy ~15 MeV
- ·Round-to-flat beam transformer
- •Double dogleg + 3.9 GHz dipole mode cavity for long.-trans. emittance exchange
- ·Quadrupoles and steering magnets along the beamline for focusing and steering
- •Extensive diagnostics (emittance, bunch length et al.)

#### A0 activities in the past 5 years

- Flagship experiments are the 6-D phase space manipulations, which include:
  - Flat beam generation (Edwards, Piot, Sun);
  - Emittance Exchange (Koeth, Johnson);
  - Longitudinal pulse shaping (Sun, Piot).
- Transverse and longitudinal beam dynamics studies (Carneiro, Bhat et al.);
- Longitudinal beam dynamics using two macroparticle bunch (Piot, Tikhoplav);
- Longitudinal bunch diagnostics using CTR (Mihalcea);
- Photocathode drive-laser research (Li, Ruan);
- Underdense plasma lens experiment (Thompson);
- Dual sweep stream camera (Lumpkin);
- CSR effects (Thangaraj, Fliller);
- OTR interferometry (Kazakevich).
- •

#### Flat beam experiment at AO



#### Achieved flat beam parameters

```
Bunch charge (nC)
                                                0.05
                                        0.50
Laser trans. rms size (mm)
                                       0.76
Laser long. rms size (ps)
                                        3
Beam energy (MeV)
                                        15.8
Q(nC)
                                        0.5
\varepsilon_{x} (mm mrad)
                                        0.41\pm0.02
\varepsilon_{v} (mm mrad)
                                        41.0 0.5
\varepsilon_{\rm v}/\varepsilon_{\rm x}
                                        100 5
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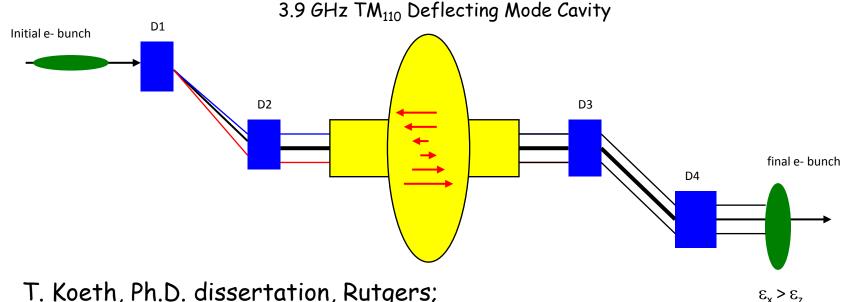
P. Piot, Y. -E Sun and K.-J. Kim, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 9, 031001 (2006)

Y.-E Sun, Ph.D. thesis, University of Chicago [Report No. Fermilab-thesis-2005-17, 2005], available at http://fnalpubs. fnal .gov/archive/thesis/fermilab-thesis-2005-17.shtml

#### Longitudinal-Transverse Emittance Exchange

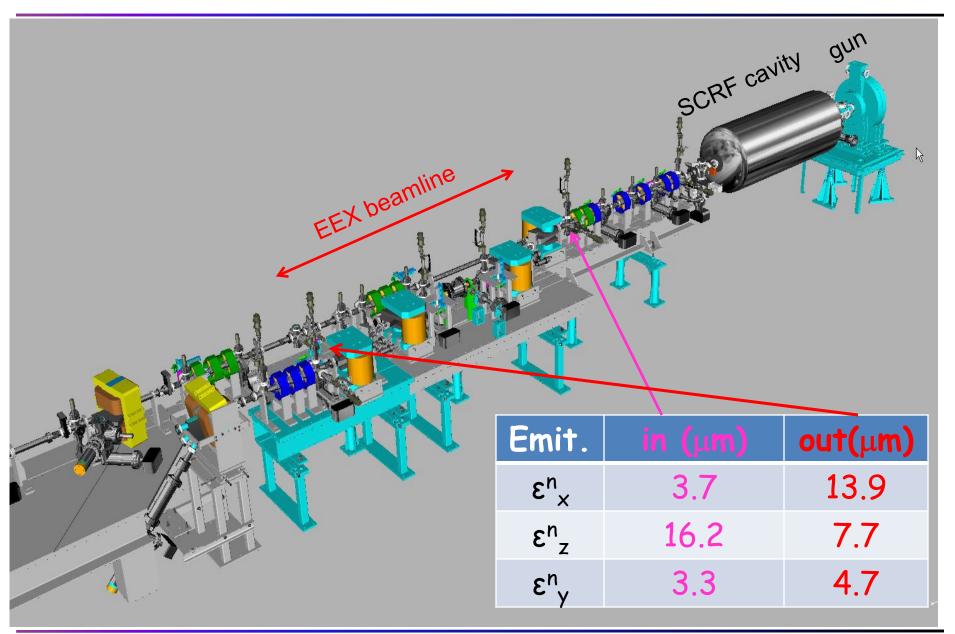
- ·Cornacchia and Emma proposed a scheme using a deflecting mode cavity in the center of a chicane for incomplete emittance exchange (2002);
- ·Kim and Sessler proposed a deflecting mode cavity between two doglegs to exchange transverse and longitudinal emittances (2005).

$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{out} = \begin{pmatrix} 0 & 0 & B_{11} & B_{12} \\ 0 & 0 & B_{21} & B_{22} \\ C_{11} & C_{12} & 0 & 0 \\ C_{21} & C_{22} & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{in}$$



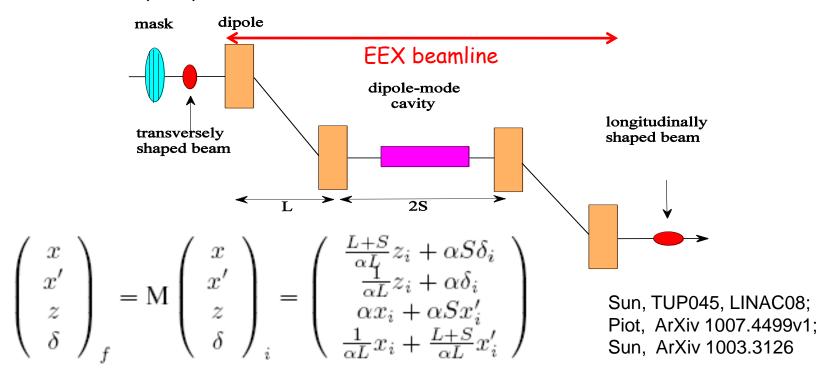
- T. Koeth, Ph.D. dissertation, Rutgers;
- A. Johnson, THPE043, IPAC 2010.

## EEX experimental results at 250 pC

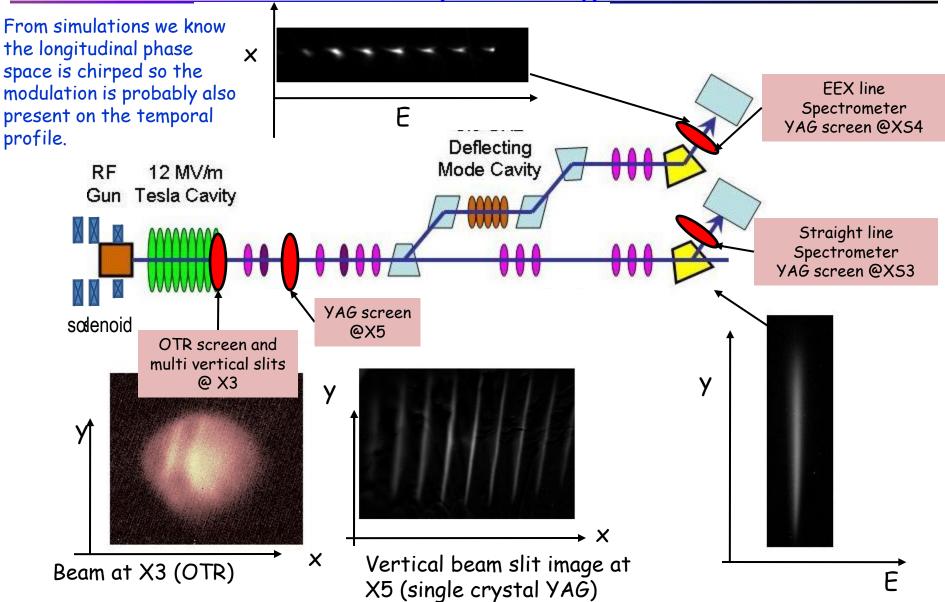


#### Multi-bunches generation via the EEX

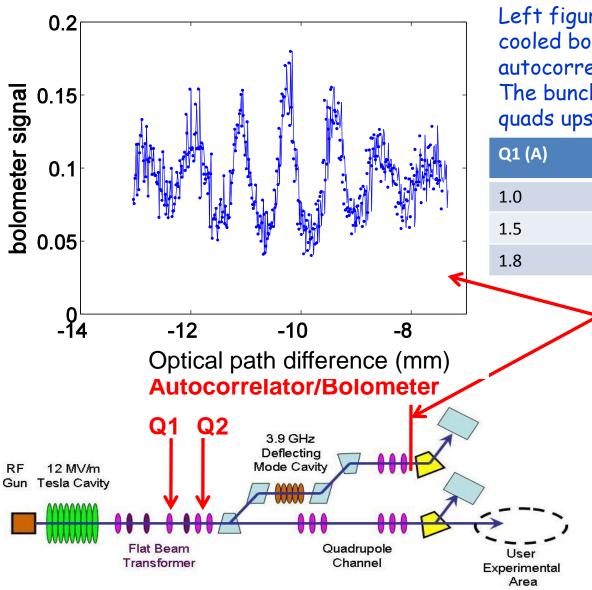
- Trains of micro-bunches with a given bunch-to-bunch separation are desired in compact light sources.
- Such bunch trains can be generated using the emittance exchange (EEX) technique.
  - Vertical multi-slits → horizontal beam profile modulation
  - Horizontal beam profile modulation  $\rightarrow$  EEX  $\rightarrow$  longitudinal phase space modulation , i.e., micro-bunch train in time



# Longitudinal pulse shaping using EEX: transverse density to energy modulation



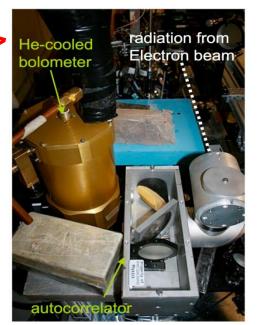
## Longitudinal pulse shaping using EEX: direct measurement of temporal modulation



Left figure: signal measured by the Hecooled bolometer as a detector of the autocorrelator.

The bunch separation can be cotrolled by quads upstream of the EEX line.

Q1 (A)	Q2 (A)	multibunch separation
1.0	-0.5	425μm (1.4 ps)
1.5	-0.5	645 μm (2.2 ps)
1.8	-0.6	840 μm (2.8 ps)



#### Previous Two Workshops on NML AARD (I)

--- Mini-workshop organized by Fermilab ---Possible Directions for Advanced Accelerator R&D at the ILC test accelerator at Fermilab Tuesday November 28th, 2006

The purpose of the workshop is to identify possible advanced accelerator R&D activities.

Topics include:

- •generation, manipulation and diagnostics of high brightness electron beams,
- ·plasma-wakefield based acceleration technique,
- ·electromagnetic structure and laser-based acceleration methods,
- radiation sources.

31 participants nationwide, 18 presentation.

#### Previous Two Workshops on NML AARD (II)

#### **FUTURE DIRECTIONS** FOR ACCELERATOR R&D AT FERMILAB

May 11-13, 2009 - Lake Geneva, WI

50 participants worldwide with many world experts

CHARGE: - solicit and evaluate ideas for a future Acc. R&D program in New Muon Lab

> - solicit and evaluate proposals for high beam intensity R&D to enhance Pr-X, ILC, Muon Collider,...

## Proposals and Suggestions for NML (1)

Experiment	Energy	proponent	Motivation/ application
Long. → transverse EEX	low	FNAL/ANL	Proof-of-principle; possible application in FELs and X-ray sources
Slit microbunching generation	low	FNAL	For wakefield investigations;
Ellipsoidal beam generation	low (egun)	NIU/FNAL	Low emittance beams
Microbunching investigations	low, high?	ANL/FNAL	Beam physics; diagnostics
ODR instrumentation development	high	ANL/FNAL	Non-invasive emittance diagnostic
Flat beam transform and image charge undulator	low	FNAL/NIU	Compact UV/ soft X-ray source
Flat beam transform	high	LANL	Proof-of-principle for MaRIE
<b>Emittance exchange</b>	high	LANL	Proof-of-principle for MaRIE
6-D muon cooling	high	IIT/FNAL	Proof-of-principle for muon collider
Optical stochastic cooling	high	IIT	Proof-of-principle; muon collider
γ-ray enhancement by crystal channeling	high	ANL	Unpolarized e <sup>+</sup> source
High gradient wakefield acceleration with dielectric structures	Low?, high?	ANL/NIU	many

## Proposals and Suggestions for NML (2)

Experiment	Energy	proponent	Motivation/ application
PIC lattice test	high	FNAL/Muons Inc	Muon collider
Reverse emittance exchange	Low?, high?	FNAL/Muons Inc	Muon collider
Dielectric Wall Accelerator section	Low? high?	FNAL	Muon collider; induction linac
Measure plasma wakes with long bunch trains	high	USC	Application to 2-beam plasma acceleration
Measure plasma wakes with laser interferometry	high	USC	Application to 2-beam plasma acceleration
Photoproduction of muons @ 300 MeV	high	FNAL	Homeland security; verify production model
Test of integrable beam optics	high	FNAL	Proof-of-principle; future high current proton machines

#### Carlsten: Emittance Partition at NML (II)

#### **Emittance Budget**

Phase space from a photoinjector is very cold – overall volume is more than sufficient for our needs:

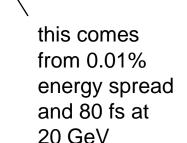
#### "typical" photoinjector at 0.5 nC:

 $\varepsilon_x \sim 0.7$  mm mrad  $\varepsilon_y \sim 0.7$  mm mrad  $\varepsilon_z \sim 1.4$  mm mrad

Somewhere in between the normalized longitudinal emittance starts growing linear with energy due to wakefields

#### our needs:

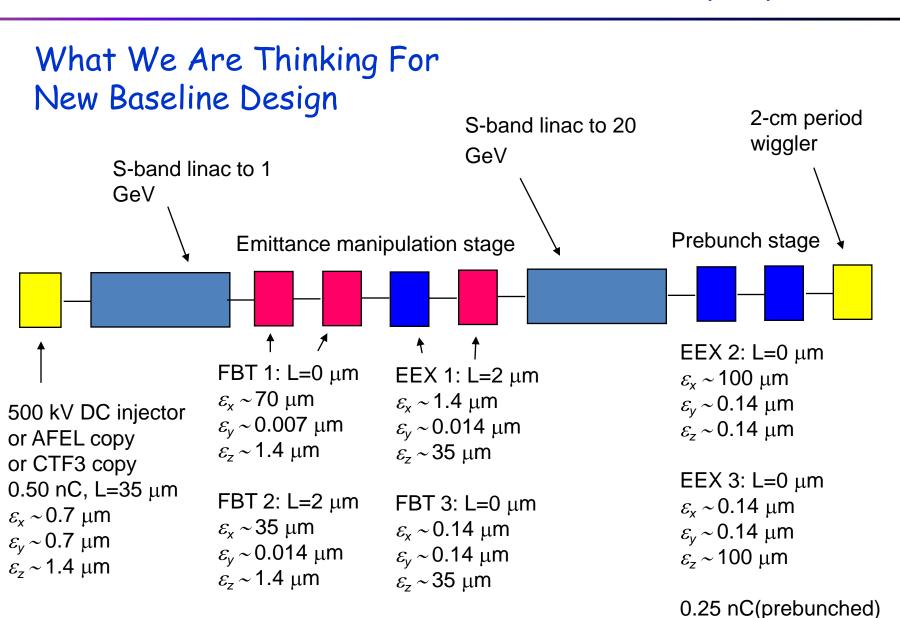
 $\varepsilon_x \sim 0.15$  mm mrad  $\varepsilon_y \sim 0.15$  mm mrad  $\varepsilon_z \sim 100$  mm mrad



Can we control the phase-space partitioning?



#### Carlsten: Emittance Partition at NML (III)



#### Carlsten: Emittance Partition at NML (IV)

#### **Beam Physics Issues**

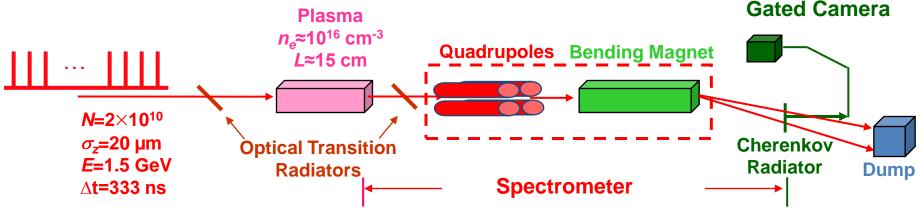
- Can we really pass angular momentum through EEX?
- Massaging beam with quads for multiple FBTs
- What energy do the wakefields dominate the longitudinal emittance? Will be exceed our longitudinal emittance budget?
- CSR through EEX better or worse than for a chicane?
- Do we need even number of EEX stages?
- What is the right trade between amount of beam loss in mask (ie bunching amplitude) and emittance for smaller bunch charges? What is the optimum prebunching wavelength?
- Is there enough time for PWA technology to mature?

#### Muggli: Plasma Wakefield Acceleration (II)

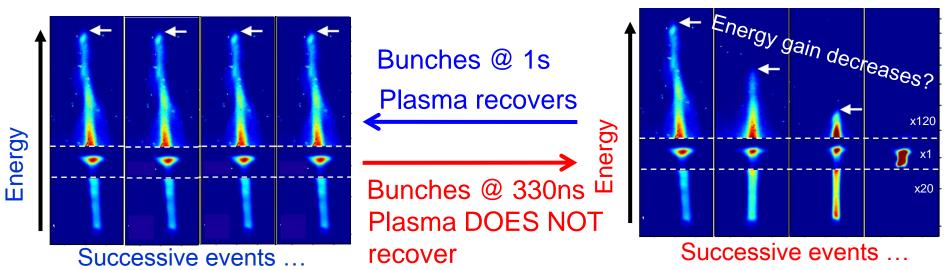
- Plasma Wakefield Accelerator (PWFA) e<sup>-</sup>/e<sup>+</sup> collider based on experimental results obtained at SLAC: 42GeV in 85cm plasma
- A significant fraction of the drive beam energy (MW) will be left in the plasma. Effect on the plasma and acceleration of a bunch train?
  - NML beams:
    - 3.2 nC/bunch; 3 MHz bunch rate; 1 ms long bunch train; 300 mm RMS bunch length; 5 Hz operation (FACET@SLAC 1-10 Hz rep rate);
    - Peak currents 10 15 kA possible;
    - single bunch intensity over 10 nC possible;
  - The beam can be compressed and focused to  $(20\times20\times20)\mu m^{3}$ ;
  - Max energy loss is 1.5GeV in 10GeV/m plasma with  $n_e=10^{17}cm-3$ ;
  - Half the bunch energy (2.5J) is deposited in a gas/plasma 1.5GeV/10GeV/m=15cm long and  $c/\omega_p$  (17 $\mu$ m) in radius (0.14mm³);
  - $-\Delta T=3700^{\circ}C$  for liquid water!!
  - This repeats 3000 times with 333ns interval, at 5Hz;
  - Effects on the plasma, gas and acceleration of a bunch train?

#### Muggli: Plasma Wakefield Acceleration (III)

- 1) Measure the energy spectrum of successive bunches in the train using a gated camera and prompt radiation (Cherenhov);
- 2) Measure beam focusing, plasma density with interferometry;



3) Possible experimental outcome:



#### Muggli: Plasma Wakefield Acceleration (IV)

- Use the unique (collider-like) format of NML bunch train to study effect of energy deposition in the plasma on acceleration;
- Directly measure effects on the bunch train:
  - Energy gain;
  - Plasma focusing;
- Require train of short (~100fs) and intense (~10kA) electron bunches;
- Study the effect as a function of bunch parameters and spacing;
- Use well-known plasma source (heat-pipe oven) and diagnostics (imaging energy spectrometer, optical transition radiation, ...);
- Experimental program supported by simulation program (PWFA and gas dynamics);
- Very important issue for plasma-based collider: very high energy density;
- Depending on the bunch charge, other effects, such as plasma ions motion could also be studied.

#### Striganov: Compact Muon Source at NML (I)

## Compact Muon Source experiment at NML

- 300 400 MeV electrons hits 10% (may be smaller) radiation length tungsten target
- □ Secondary 0 degree neutral particles (gammas) interact with 1 cm carbon targets. Charged particles created on tungsten target could be removed by sweeping magnets
- □ "Surface" muon beams, from positive pions stopping and decaying in the target surface can be measured at few angles relative to gamma direction
- Measurement of "surface" muons and background particles could be useful for confirmation/development of CMS concept

#### Striganov: Compact Muon Source at NML (II)

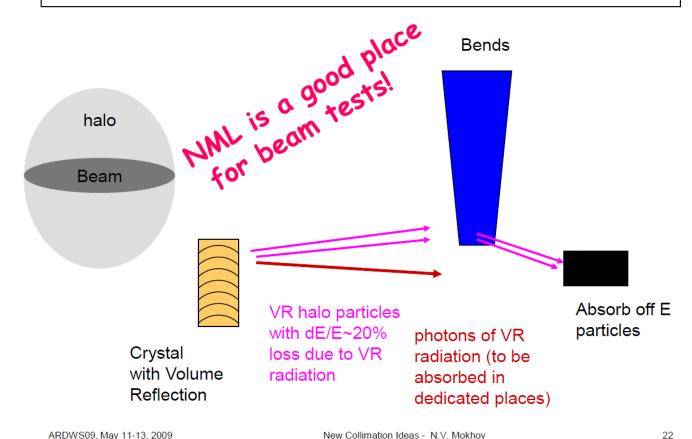
Zero angle bremsstrahlung beam at NML could be used to perform several experiments with secondary muons:

- measurement of energy distributions of fast muons produced in interaction of gammas with thick (20-30 radiation length target) to check muon photo-production models
- □ measurement of number of low energetic ("surface") muons produced in interaction of gammas with thin low Z target to check Compact Muon Source concept
- □ proof of principle CMS experiment

#### Mokhov: Beam Collimation Test at NML (I)

Experiment at NML on volume reflection radiation as an interesting possibility for e+ e- beam collimation.

e<sup>+</sup> e<sup>-</sup> Beam Collimation Based on VR radiation



ARDWS09, May 11-13, 2009

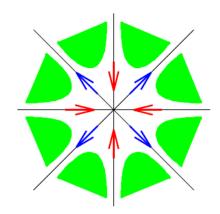
New Collimation Ideas - N.V. Mokhov

#### Mokhov: Beam Tail Folding at NML (I)

Experiment at NML on beam tail folding with octupole doublet.

#### Nonlinear Handling of Beam Tails

- One wants to focus beam tails but not to change the core of the beam
  - use **nonlinear** elements
- Several nonlinear elements need to be combined to provide focusing in all directions
  - (analogy with strong focusing by FODO)
- Octupole Doublets (OD) can be used for nonlinear tail folding



Single octupole focus in planes and defocus on diagonals.

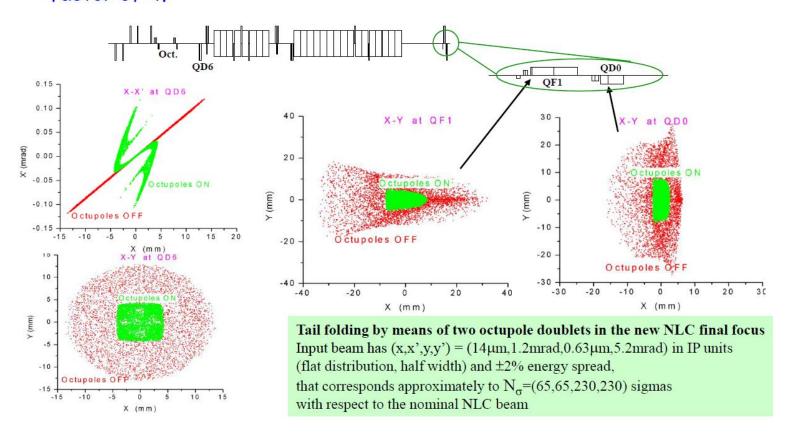
An octupole doublet can focus in all directions!

Courtesy A. Seryi

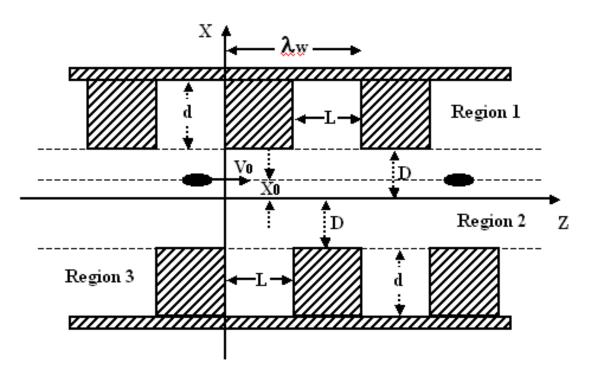
#### Mokhov: Beam Tail Folding at NML (II)

#### Predicted Tail Folding Effect

Two octupole doublets give tail folding by  $\sim 4$  times in terms of beam size in FD. This can lead to relaxing collimation requirements by  $\sim a$  factor of 4.



#### Image Charge Undulator (ICU) (I)



Y. Zhang et al, NIM A, 507 (2003) 459 – 463; PAC 2003 Proceedings, Page 941.

- 1. Two pieces of identical periodic metal grating;
- 2. Asymmetric arrangement;
- 3. A flat electron beam passes in between the gratings.

#### Understanding of the ICU (II)

- The electron beam induces its image charge in the metal gratings, and the image charge applies a Lorentz force (wakefield) on the electron beam;
- Due to the periodic gratings, the image charge wakefield alternates like in a conventional magnetic undulator;
- This process leads to the undulating motion of the electron beam;
- The rest of the radiation mechanism follows like in a magnetic undulator. For example, the radiation wavelength is given by

$$\lambda = \frac{\lambda_g}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right).$$

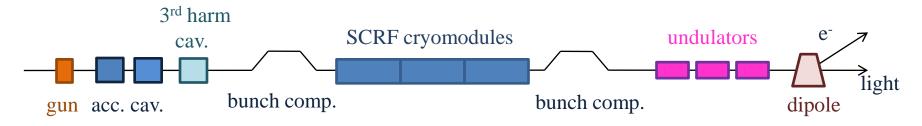
- Because  $\Lambda_g$  can be much smaller in ICU, much shorter radiation wavelength is possible in ICU for the same drive beam energy.

### Flat beam and image charge undulator (III)

- A challenging experiment due to the extremely small beam size required in the image charge undulator;
- First step will be passing a flat beam between two pieces of flat metal surface;
- Next step: spontaneous ICU radiation
  - Observe spontaneous radiation;
  - Characterize energy spread generated on the beam due to the wake;
  - Do this scanning various key parameters:
    - Beam energy;
    - · Undulator gap;
    - · Bunch charge.

#### FEL@NML (Piot, Lumpkin et al.)?

- Photocathode RF gun, supercondcuting RF acceleration structures, two stage magnetic bunch compression...
  - These are typical components of modern accelerator-driving Free Electron Laser (FEL) facility;
- When operated at very low charge (<50 pC), NML can produce beam supporting x-ray FEL oscillator, as well as atosecond SASE FEL. A UChicago-FNAL proposal by Piot et al. has recently been funded for this study.



 At 1 nC mode, The beam quality at NML can support an exciting FEL R&D program.

#### Summary

- NML is committed to establish a committee reviewed, proposaldriven AARD program for its users. We have organized workshops in the past years which gathered tens of proposed experiments.
- The proposed experiments represent serious interests in NML from the high energy physics community in the U.S. as well as in the world. We have an opportunity to advance the physics and technology in accelerator field by choosing carefully, with the guidance from a NML AARD Advisory Committee, some of the proposed experiments to carry forward.
- We are open for new proposals which take advantage of the unique NML beam properties.
- Last but not least, NML will be an excellent facility to train accelerator scientists and engineers.